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955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: Apollo 9 POGO Stability Analysis - Case 320

DATE: February 7, 1969

FROM: A. T. Ackerman
J. J. O'Connor
H. E. Stephens

ABSTRACT

The POGO II computer program was used to examine the S-IC POGO stability of the Apollo 9 vehicle (SA-504/CSM-104/LM-3). The Rocketdyne F-1 engine transfer functions were used and modified to incorporate the MSFC experimental data for the fuel-side gain. Boeing coupled modal structural data were used to select the nine modes with the greatest longitudinal components. The open-loop margin was calculated by opening the outboard engine thrust. The results show engine mode and tank mode margins as small as 3 to 4 db for Apollo 9. While these margins are small, they are very close to those calculated for Apollo 8 which flew without S-IC POGO with the four accumulator fix. Therefore, the same remedy should be successful for Apollo 9.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The POGO II computer program was used to examine the S-IC POGO stability of the Apollo 9 vehicle (SA-504/CSM-104/LM-3). The results were presented to the MSFC POGO Working Group Meeting on January 27. Since then certain modifications were made in our analysis which slightly affected the stability margins near the end of the S-IC boost phase. Figure 4 shows the updated margins.

II. ENGINE TRANSFER FUNCTIONS

The fuel side engine transfer function relating change of thrust, T, to change in fuel suction pressure, P_{sf}, was adjusted on the basis of the MSFC F-1 engine firing tests. An expression in the form

$$\frac{\partial T}{\partial P_{sf}}(s) = \frac{K\ (s-\omega_1)\ (s+\omega_2)}{(s+\omega_3)(s^2 + 2\delta\ \omega_4 s + \omega_4^{\ 2})}$$

was fitted to the phase data shown in Figure 1; the resulting amplitude comparison is shown in Figure 2. The amplitude data points were lowered by 3.2 db to account for the LOX-side coupling present in the engine under test. The data points were further reduced by 4.5 db to account for the frequency drop-off of thrust, used in the analysis, relative to the chamber pressure, actually measured in the test. (The Mod A curve fit did not account for this second correction.) The MSFC curve fit is also shown in Figures 1 and 2. The numerical values for both curves are:

	K	$\frac{\omega_1}{2\pi}$	$\frac{\omega_2}{2\pi}$	$\frac{\omega_3}{2\pi}$	$\frac{\omega_4}{2\pi}$	δ
Mod B	388	7.0	199.0	3.0	11.0	0.25
MSFC	15,109	1.9	9.6	0.9	13.4	0.375

It should be noted that this curve fitting approach incorporates the experimental data into the analysis. It is used in lieu of increasing the (unmodified) Rocketdyne transfer function by the 1.8 factor.

III. STRUCTURAL DATA

Our POGO stability analysis uses nine flexible body modes plus the rigid body mode. The Boeing* longitudinal modal data were studied to insure that modes of the highest gain longitudinal components (at any time point) were incorporated in the analysis. A study of the mode shapes was then made to track these modes for all time points. The frequencies of the selected modes are shown in Figure 3 with the original Boeing mode numbers shown on the curves.

IV. STABILITY MARGINS

The stability margins, shown in Figure 4, are based on opening the loop at the outboard engines to be consistent with the MSFC approach. It is known that some of the margins are sensitive to the fuel-side engine gain. However, the difference between the Mod B and the MSFC curve-fitted gain is only one or two db. The MSFC gain leads to slightly lower margins due to its slightly higher gain, as seen on Figure 2.

The frequencies of the zero-phase gain points are plotted on Figure 5. The "engine mode" margin is seen to wander around the several structural modes in the 15 to 17 hertz region. The other margins do not seem to be related to specific structural modes. This feature seems peculiar to the use of the Rocketdyne engine transfer functions; the use of our own transfer function, derived from engine component analysis, results in margins which track the structural frequencies. The reason for this may be related to the non-minimum phase feature of the Rocketdyne transfer function due to the minus sign on the ω_1 term. Examination of the Nyquist plots for fixed time points tend to confirm this possibility.

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*Saturn V AS-504 Coupled Dynamic Characteristics (IX Volumes) Boeing D5-15774-4, December 2, 1968.

The minus sign was introduced by Rocketdyne to relate the frequency response (calculated by a digital simulation of component-derived transfer functions) to the steady state engine characteristic. An increase in fuel flow actually leads to a decrease in thrust due to lower combustion temperature. This subtle interaction with the gas generator boot-strap loop had been established by many steady-state measurements of actual hardware. The only dynamic data ever taken are shown in Figures 1 and 2. The Rocketdyne model did not accurately predict the amplitude or the phase in the 10 hertz region, and therefore the (non-minimum phase) transfer function might be questioned.

The effect of the additional phase shift is to increase the amplitude margin, that is, it tends to phase stabilize the system. However, this phase-shift effect disappears at the minimum margin (T + 130 seconds) which occurs exactly at the frequency of the first tank mode. The margin at T + 130 seconds is smaller than the margin at any other time point, with or without phase stabilization. In other words, we get the same value of minimum margin with either Rocketdyne or our own engine transfer functions.

The LOX and fuel suction line frequencies are shown in Figure 6. The presence of the accumulators in the outboard LOX suction lines lowers the first resonant frequency to the 1.5 to 2 hertz region. The unmodified inboard LOX line has the original 4 to 5 hertz resonance. Neither of these lines lead to any stability margin smaller than 40 db. The second resonance of the outboard LOX line in the 14 to 18 hertz region leads to the "engine mode" margin. The fuel lines resonances in the 10 to 12 hertz range lead to the other margins which are associated with the higher tank mode near lift-off, with the first tank mode near center-engine cut-off (T + 134 seconds) and with the second body mode near burn-out. This mode might be called the "fuel-line" mode and is the reason that the fuel-side engine gain characteristic is so important.

V. CONCLUSION

This POGO stability analysis, like any other, should be considered as indicative, not definitive. There are still questions about the choice of structural modes, structural damping, the calculation of tank bottom pressures and the suction line frequencies -- both the fundamentals and the harmonics. Even the method of measuring the margin has several possibilities -- open loop at outboard engine thrust, open loop at structural acceleration, or closed loop damping.

With these uncertainties, the 3 to 4 db margins for Apollo 9 shown on Figure 4 are small indeed. However, a similar analysis of the Apollo 8 vehicle produced almost exactly equal margins. This indicates that the vehicles are very similar, at least as our analysis capability is concerned, and perhaps the analysis technique has a certain amount of built-in conservatism. The successful flight demonstration of the four accumulator fix on Apollo 8 indicates that it should suppress S-IC POGO on Apollo 9.

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Attachments
Figures 1 to 6

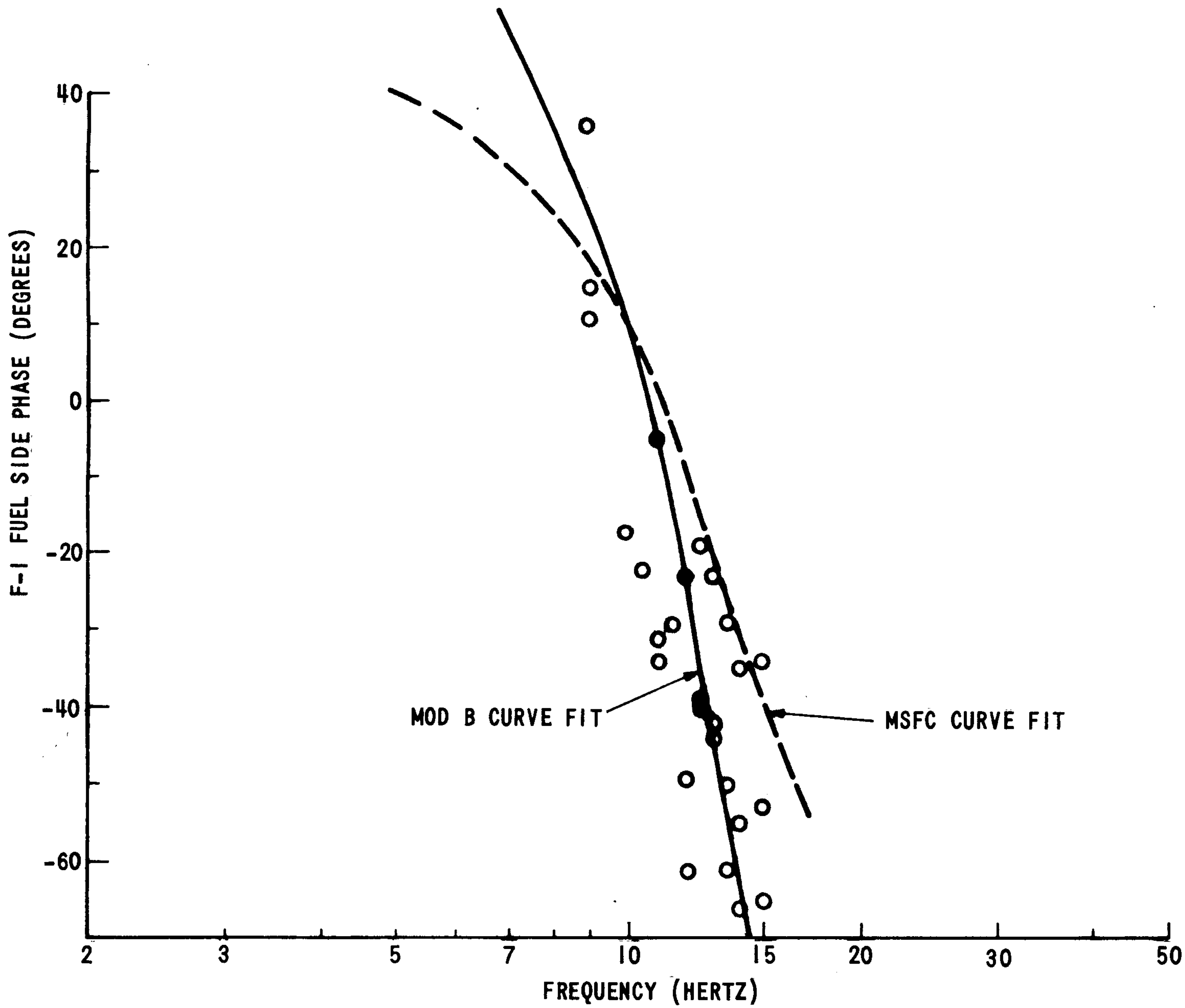

FIGURE 1 - F-1 ENGINE FUEL SIDE PHASE DATA

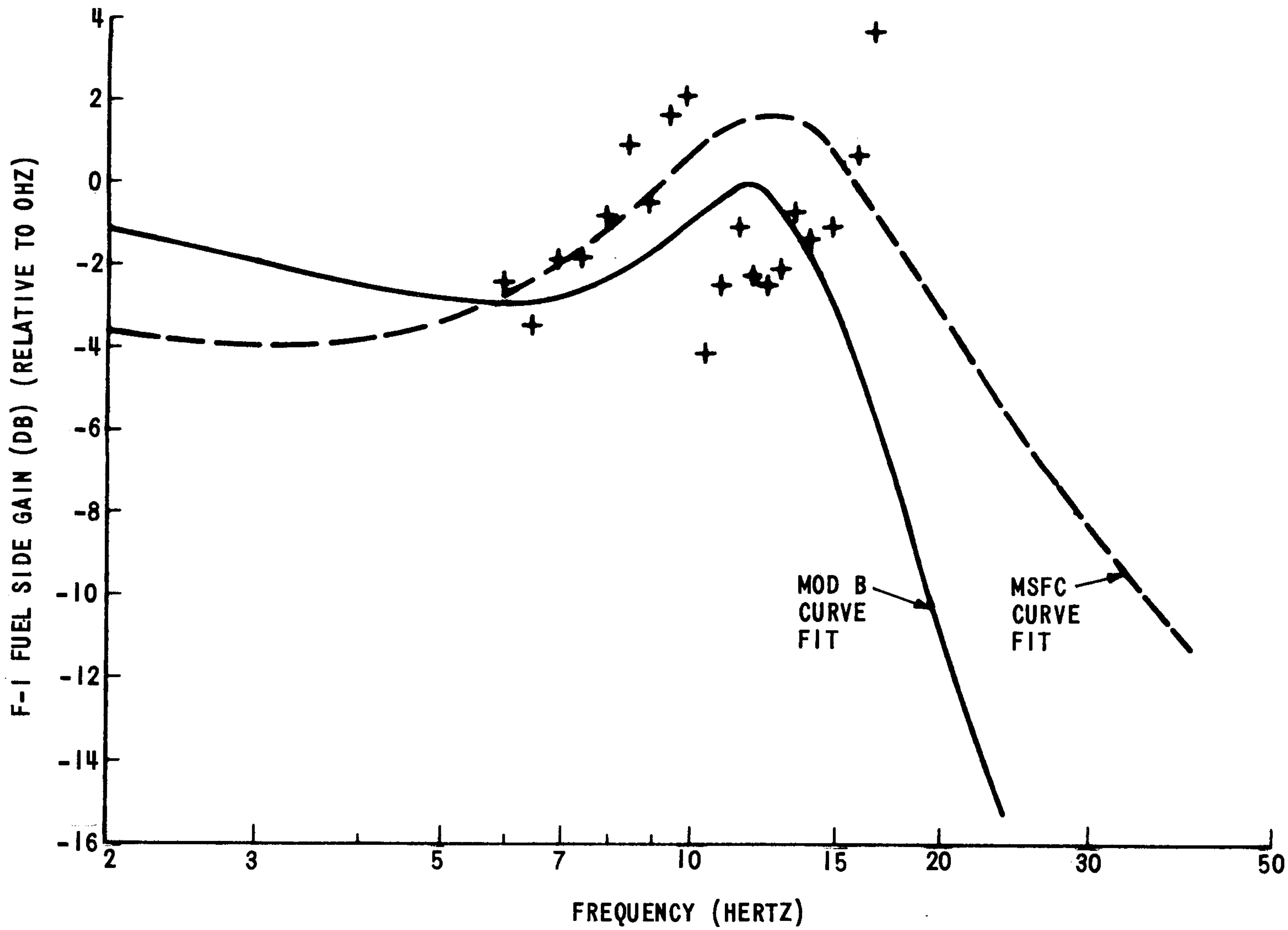

FIGURE 2 - F-1 ENGINE FUEL SIDE AMPLITUDE DATA

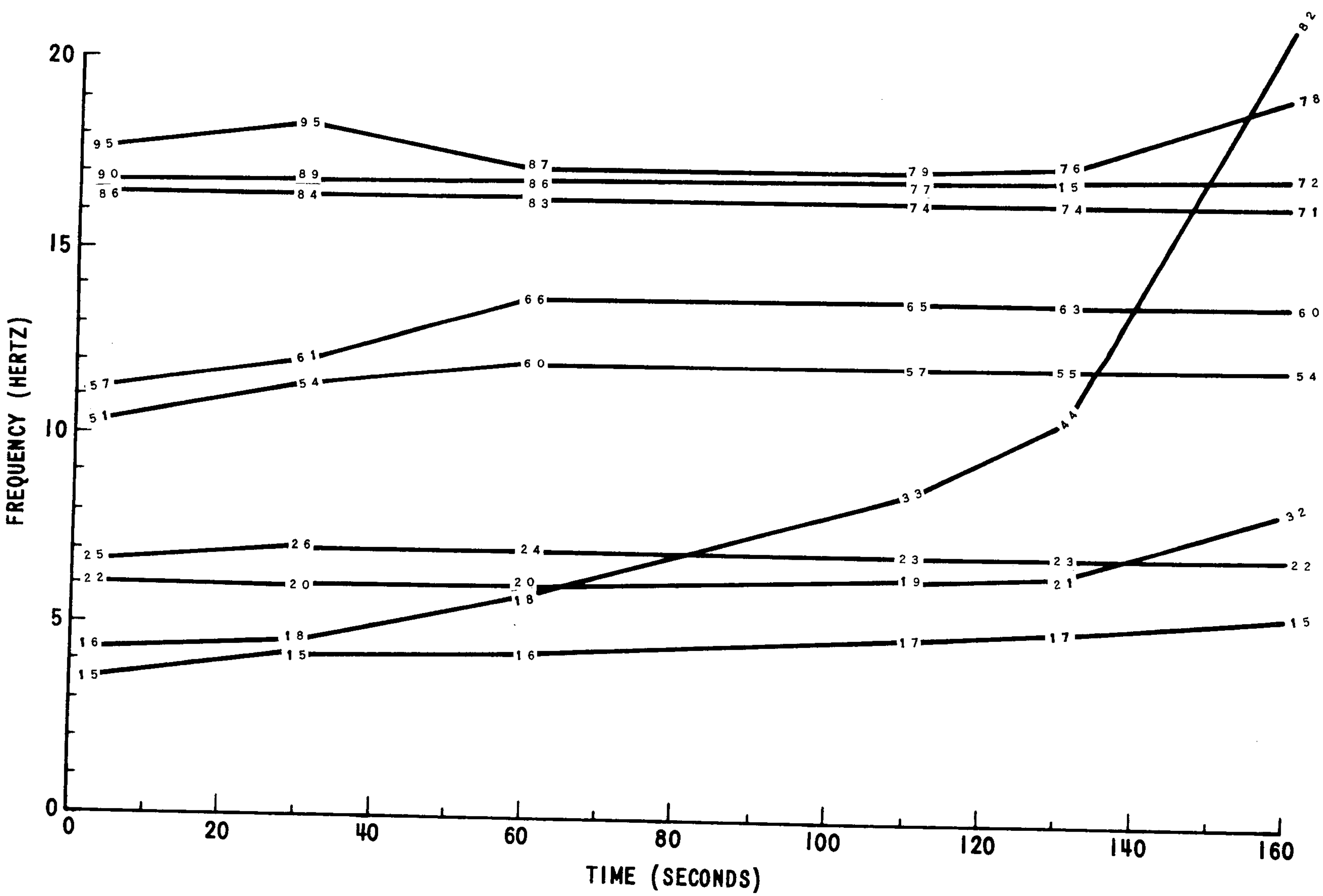

FIGURE 3 - APOLLO 9 LONGITUDINAL FREQUENCIES

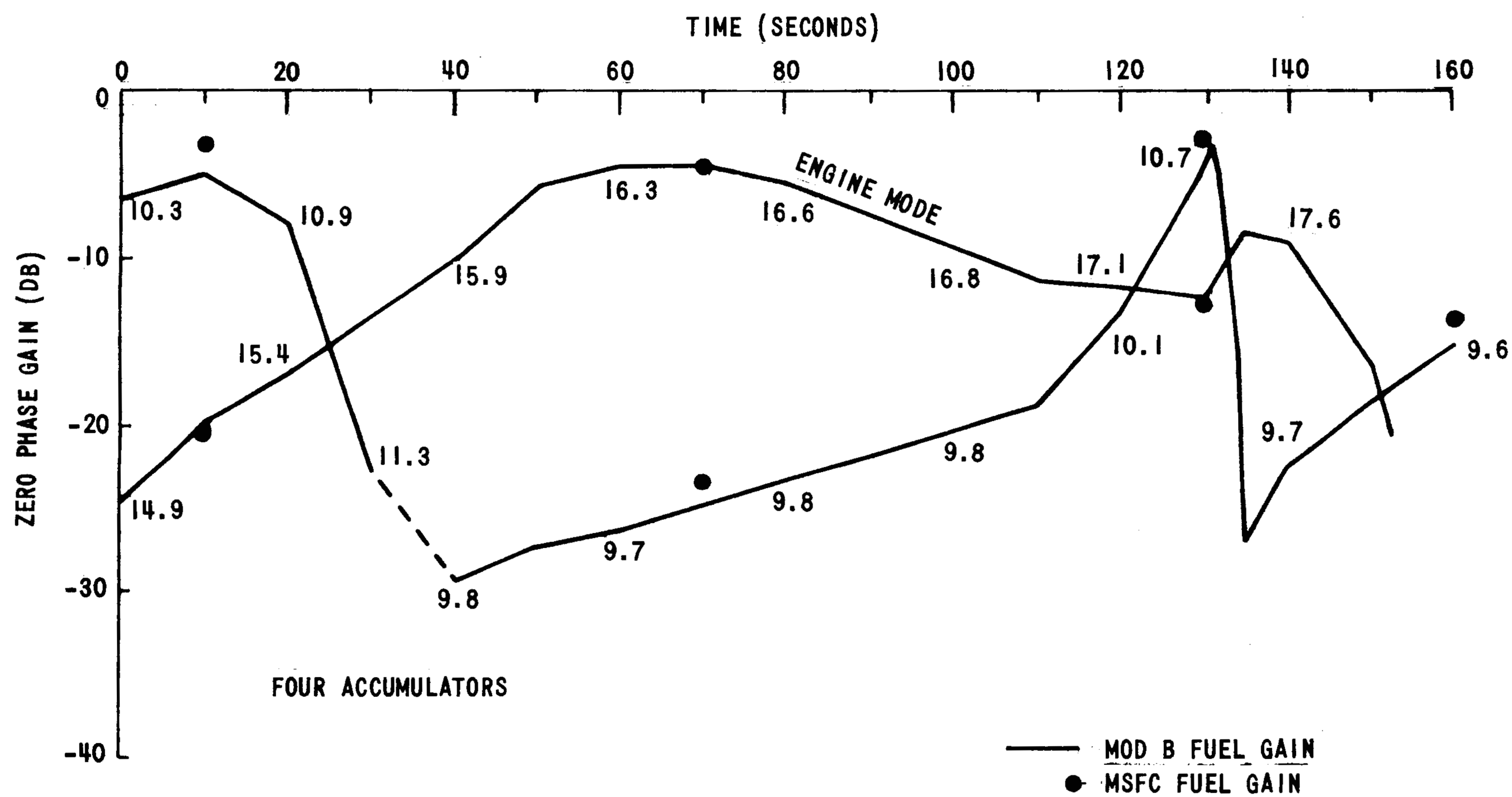

FIGURE 4 - APOLLO 9 POGO STABILITY MARGINS

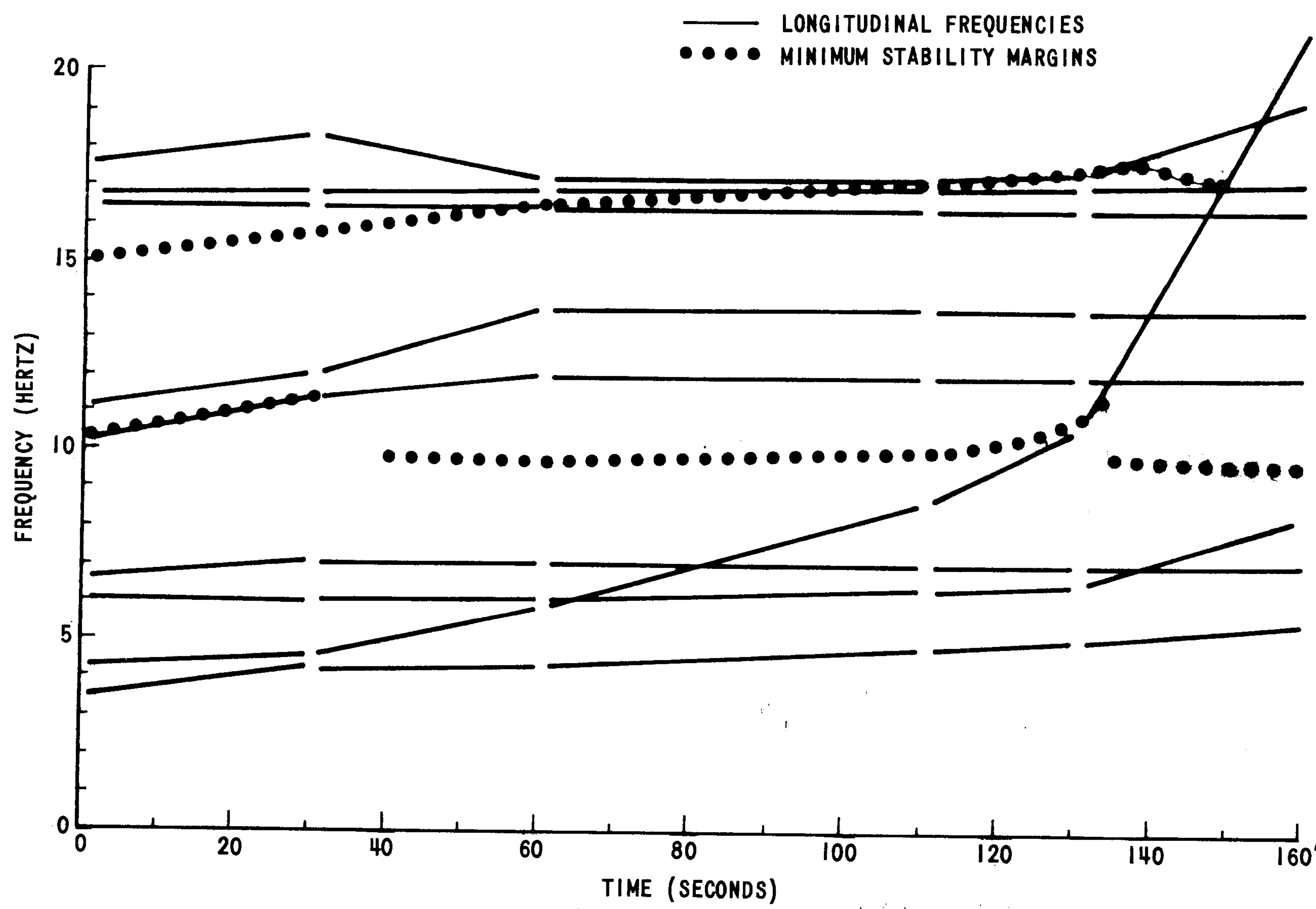

FIGURE 5 - APOLLO 9 MINIMUM STABILITY FREQUENCIES

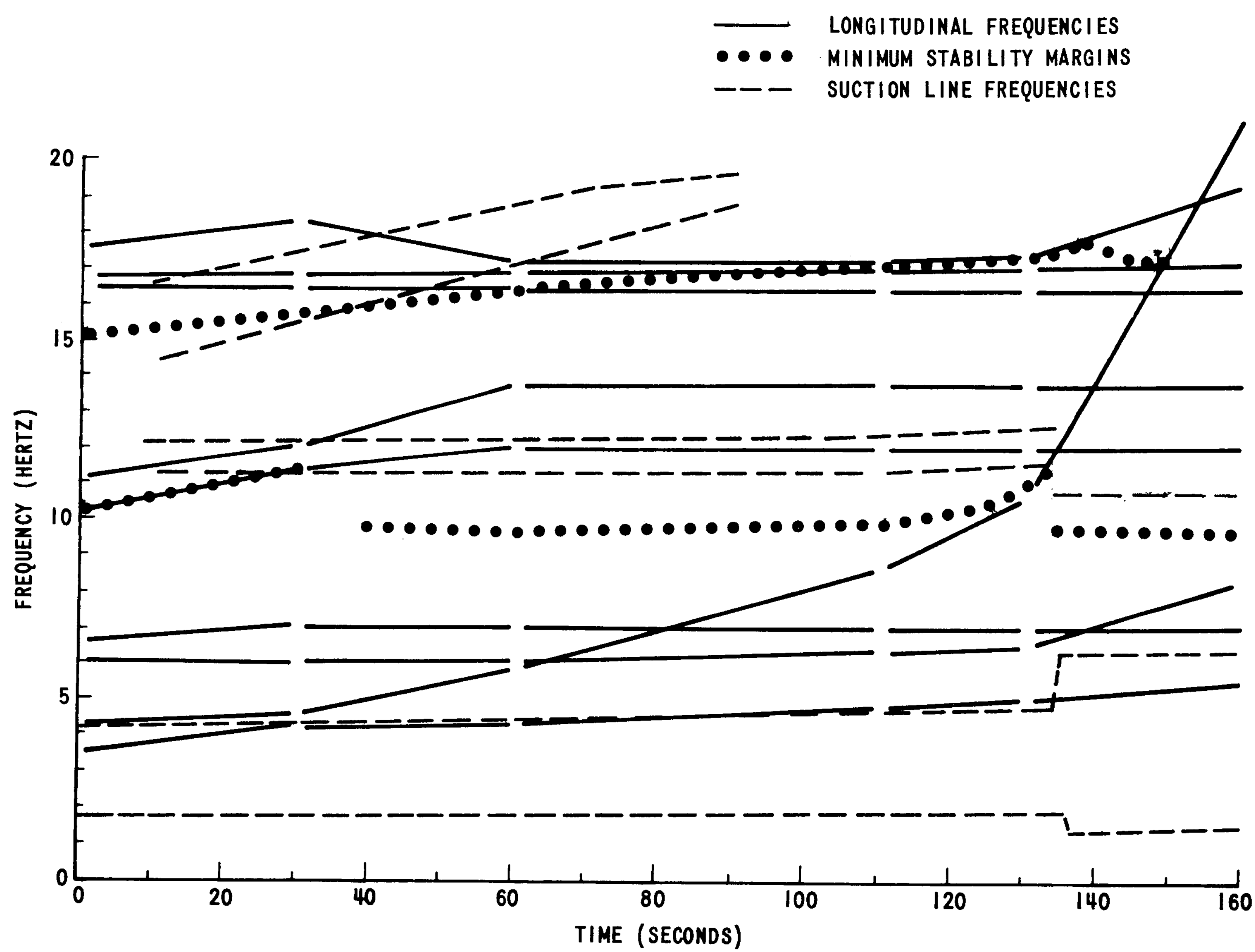

FIGURE 6 - APOLLO 9 SUCTION LINE FREQUENCIES

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